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AUTHOR(S):

DUMAN, EMEL YAVUZ; OWA, SHIGEYOSHI

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# RADIUS PROBLEMS FOR INVERSE FUNCTIONS CONCERNING WITH BI-UNIVALENT FUNCTIONS

EMEL YAVUZ DUMAN AND SHIGEYOSHI OWA

**ABSTRACT.** For bi-univalent functions of univalent functions in the open unit disc, there are some coefficient estimates. In the present paper, new radius problems for convex functions and starlike functions concerning with bi-univalent functions are discussed.

## 1. INTRODUCTION

Let  $\mathcal{A}(r)$  be the class of functions  $f(z)$  of the form

$$(1.1) \quad f(z) = z + \sum_{k=2}^{\infty} a_k z^k$$

that are analytic in the open unit disc  $U(r) = \{z \in \mathbb{C} \mid |z| < r\}$ .

Let  $\mathcal{S}$  denote the subclass of  $\mathcal{A}(1)$  consisting of  $f(z)$  which are univalent in the open unit disc  $U(1)$ . A function  $f(z) \in \mathcal{A}(1)$  is said to be starlike with respect to the origin in  $U(1)$  if  $f(z)$  satisfies

$$(1.2) \quad \Re \left( \frac{zf'(z)}{f(z)} \right) > 0 \quad (z \in U(1)).$$

We denote by  $\mathcal{S}^*$  the class of all such starlike functions  $f(z)$ . Further, let  $\mathcal{K}$  be the subclass of  $\mathcal{A}(1)$  consisting of functions  $f(z)$  which satisfy

$$(1.3) \quad \Re \left( 1 + \frac{zf''(z)}{f'(z)} \right) > 0 \quad (z \in U(1)).$$

A function  $f(z)$  in the class  $\mathcal{K}$  is said to be convex in  $U(1)$ .

It is well-known that

$$(1.4) \quad f(z) = \frac{z}{(1-z)^2} = z + \sum_{k=2}^{\infty} k z^k$$

is the extremal function for  $\mathcal{S}^*$ , and that

$$(1.5) \quad f(z) = \frac{z}{1-z} = z + \sum_{k=2}^{\infty} z^k$$

is the extremal function for  $\mathcal{K}$  (see [2], [3]).

We also note that  $\mathcal{K} \subset \mathcal{S}^* \subset \mathcal{S} \subset \mathcal{A}(1)$ .

Since  $\mathcal{S}$  is the class of univalent functions  $f(z) \in \mathcal{A}(1)$ , for each function  $w = f(z)$  in  $\mathcal{S}$ , there exists an inverse function  $f^{-1}(w)$  of  $f(z)$ . If  $f(z) \in \mathcal{S}$  and  $f^{-1}(w)$  has a univalent analytic continuation to  $|w| < 1$ , then  $f(z)$  is said to be bi-univalent in  $U(1)$ . The concept of bi-univalent functions was given by Lewin

[5], and studied by Brannan and Taha [1], Xu, Gui and Srivastava [6], and Xu, Xiao and Srivastava [7]. Xu, Gui and Srivastava [6] showed that functions

$$\frac{z}{1-z}, -\log(1-z), \frac{1}{2} \log \left( \frac{1+z}{1-z} \right)$$

are bi-univalent in  $\mathbb{U}(1)$ , and that functions

$$z - \frac{1}{2}z^2, \frac{z}{1-z^2}$$

are not bi-univalent in  $\mathbb{U}(1)$ .

Recently, Hayami and Owa [4] have given the following theorem for bi-univalent functions.

**Theorem A.** *If  $f(z) \in \mathcal{S}$ , then it follows that  $f(\mathbb{U}(1)) \not\subset \mathbb{U}(1)$  and  $f(\mathbb{U}(1)) \not\supset \mathbb{U}(1)$  unless  $f(z) = z$ .*

But, we know that all functions  $f(z) \in \mathcal{S}$  include the open disc  $\mathbb{U}(1/4) = \{z \in \mathbb{C} \mid |z| < 1/4\}$ . Therefore, we consider the subclass  $\mathcal{S}(r)$  of  $\mathcal{A}(r)$  consisting of  $f(z)$  which are univalent in  $\mathbb{U}(r)$ .

Since  $f(0) = 0$  for  $f(z) \in \mathcal{S}(r)$ , there exists an open disc such that

$$f(\mathbb{U}(r)) \supset \{z \mid |z| < \max_{|z| < r} |f(z)|\}.$$

For such an open disc, we consider the inverse function  $f^{-1}(w)$  of  $f(z)$  such that  $f^{-1}(0) = 0$ .

In view of the above concept, we can consider

$$\begin{aligned} w_1(z) &= f(z) & (z \in \mathbb{U}(r_1)), \\ w_2(z) &= f^{-1}(w_1) & (z \in \mathbb{U}(r_2)), \\ w_3(z) &= f^{-1}(w_2) & (z \in \mathbb{U}(r_3)), \end{aligned}$$

and

$$w_n = f^{-1}(w_{n-1}) \quad (z \in \mathbb{U}(r_n)).$$

## 2. PROPERTIES FOR CONVEX FUNCTIONS

We first consider the inverse function  $f^{-1}(w)$  of the automorphism  $w = f(z)$ .

**Theorem 2.1.** *Let us define*

$$(2.1) \quad w_1 = f(z) = \frac{z}{1-az} \quad (|z| < 1/a)$$

for some real  $a$  ( $0 < a \leq 1$ ). Then  $w_n = f^{-1}(w_{n-1})$  satisfies

$$(2.2) \quad w_n = \frac{w_{n-1}}{1 + (-1)^n a w_{n-1}} \quad (|w_{n-1}| < 1/(na))$$

and

$$(2.3) \quad \left| w_n + \frac{(-1)^n}{(n^2-1)a} \right| < \frac{n}{(n^2-1)a} \quad (n = 2, 3, 4, \dots).$$

*Proof.* For  $w_1$ , we see that

$$(2.4) \quad |z| = \left| \frac{w_1}{1 + a w_1} \right| < \frac{1}{a}$$

which gives that

$$\Re w_1 > -\frac{1}{2a} \quad (|z| < 1/a).$$

Next, we consider

$$(2.5) \quad w_2 = f^{-1}(w_1) = \frac{w_1}{1 + aw_1} \quad (|w_1| < 1/(2a)).$$

Noting that

$$(2.6) \quad |w_1| = \left| \frac{w_2}{1 - aw_2} \right| < \frac{1}{2a},$$

we have that

$$(2.7) \quad \left| w_2 + \frac{1}{3a} \right| < \frac{2}{3a}.$$

Therefore, the result holds true for  $n = 2$ .

Suppose that (2.2) and (2.3) hold true for  $n$ . Then, since

$$(2.8) \quad |w_{n-1}| = \left| \frac{w_n}{1 - (-1)^n aw_n} \right| < \frac{1}{na},$$

we obtain that

$$(2.9) \quad w_{n+1} = \frac{w_n}{1 + (-1)^{n+1} aw_n}$$

and (2.3) shows us that  $w_n$  includes the open disc  $|w_n| < 1/((n+1)a)$ . Therefore,  $w_{n+1}$  satisfies that

$$(2.10) \quad |w_n| = \left| \frac{w_{n+1}}{1 - (-1)^{n+1} aw_{n+1}} \right| < \frac{1}{(n+1)a}.$$

Noting that

$$(2.11) \quad (n+1)^2 a^2 |w_{n+1}|^2 < |1 - (-1)^{n+1} aw_{n+1}|^2,$$

we show that

$$(2.12) \quad \left| w_{n+1} + \frac{(-1)^{n+1}}{((n+1)^2 - 1)a} \right| < \frac{n+1}{((n+1)^2 - 1)a}.$$

Thus, by the mathematical induction, we complete the proof of the theorem.  $\square$

Making  $a = 1$  in Theorem 2.1, we have

**Corollary 2.2.** *The extremal function  $f(z)$  given by (1.5) in  $|z| < 1$  satisfies*

$$(2.13) \quad w_n = \frac{w_{n-1}}{1 + (-1)^n w_{n-1}} \quad (|w_{n-1}| < 1/n)$$

and

$$(2.14) \quad \left| w_n + \frac{(-1)^n}{n^2 - 1} \right| < \frac{n}{n^2 - 1} \quad (n = 2, 3, 4, \dots).$$

### 3. PROPERTIES FOR STARLIKE FUNCTIONS

The next our result for the inverse function  $f^{-1}(w)$  of starlike functions is contained in

**Theorem 3.1.** *Let us define*

$$(3.1) \quad w_1 = f(z) = \frac{z}{(1-z)^2} \quad (|z| < 1).$$

*Then  $w_n = f^{-1}(w_{n-1})$  satisfies*

$$(3.2) \quad w_{2n} = \frac{1 + 2w_{2n-1} - \sqrt{1 + 4w_{2n-1}}}{2w_{2n-1}} \quad (|w_{2n-1}| < 1/(4n))$$

*and*

$$(3.3) \quad w_{2n+1} = \frac{w_{2n}}{(1 - w_{2n})^2} \quad (|w_{2n}| < 2n + 1 - 2\sqrt{n(n+1)})$$

*for  $n = 1, 2, 3, \dots$ .*

*Proof.* For  $n = 1$ ,

$$(3.4) \quad w_2 = \frac{1 + 2w_1 - \sqrt{1 + 4w_1}}{2w_1} \quad (|w_1| < 1/4).$$

Since

$$(3.5) \quad |w_2| = \left| 1 + \frac{1 - \sqrt{1 + 4w_1}}{2w_1} \right| \quad (|w_1| < 1/4),$$

we obtain that

$$(3.6) \quad \min_{|w_1|=1/4} |w_2| = 1 + 2(1 - \sqrt{2}) = 3 - 2\sqrt{2}.$$

Therefore, we have that

$$(3.7) \quad w_3 = \frac{w_2}{(1 - w_2)^2} \quad (|w_2| < 3 - 2\sqrt{2}).$$

Since

$$(3.8) \quad w_3 = \frac{1}{w_2 + \frac{1}{w_2} - 2} \quad (|w_2| < 3 - 2\sqrt{2}),$$

let us consider

$$(3.9) \quad w_2 + \frac{1}{w_2} = u + iv$$

for  $|w_2| = 3 - 2\sqrt{2}$ . This implies that

$$(3.10) \quad \frac{u^2}{36} + \frac{v^2}{32} = 1.$$

Thus, we obtain that

$$(3.11) \quad \min_{|w_2|=3-2\sqrt{2}} |w_3| = \frac{1}{8}.$$

Therefore, (3.2) and (3.3) are hold true for  $n = 1$ . Next, we assume that (3.2) and (3.3) are true for  $n = j$ , such that

$$(3.12) \quad w_{2j} = \frac{1 + 2w_{2j-1} - \sqrt{1 + 4w_{2j-1}}}{2w_{2j-1}} \quad (|w_{2j-1}| < 1/(4j))$$

and

$$(3.13) \quad w_{2j+1} = \frac{w_{2j}}{(1 - w_{2j})^2} \quad (|w_{2j}| < 2j + 1 - 2\sqrt{j(j+1)}).$$

It follows from (3.13) that  $w_{2j} = u + iv$  satisfies

$$(3.14) \quad \frac{u^2}{4(2j+1)^2} + \frac{v^2}{16j(j+1)} = 1$$

for  $|w_{2j}| = 2j + 1 - 2\sqrt{j(j+1)}$ . This gives us that

$$(3.15) \quad \min_{|w_{2j}|=2j+1-2\sqrt{j(j+1)}} |w_{2j+1}| = \frac{1}{4(j+1)}.$$

Thus, we have that

$$(3.16) \quad w_{2(j+1)} = \frac{1 + 2w_{2j+1} - \sqrt{1 + 4w_{2j+1}}}{2w_{2j+1}} \quad (|w_{2j+1}| < 1/(4(j+1))).$$

Furthermore, since

$$(3.17) \quad |w_{2(j+1)}| = \left| 1 + \frac{1 - \sqrt{1 + 4w_{2j+1}}}{2w_{2j+1}} \right| \quad (|w_{2j+1}| < 1/(4(j+1))),$$

we also have that

$$(3.18) \quad \min_{|w_{2j+1}|=\frac{1}{4(j+1)}} |w_{2(j+1)}| = 2(j+1) + 1 - 2\sqrt{(j+1)(j+2)}.$$

Consequently, (3.2) and (3.3) are hold true for  $n = j + 1$ . Thus, applying mathematical induction, we complete the proof of the theorem.  $\square$

Finally, we consider the following function

$$(3.19) \quad w_1 = \frac{z}{(1 - az)^2} \quad (0 < a \leq 1)$$

for  $|z| < 1$ . Since

$$(3.20) \quad \Re \left( \frac{zw'_1}{w_1} \right) = \Re \left( \frac{1 + az}{1 - az} \right) > \frac{1 - a}{1 + a},$$

$w_1$  is starlike with respect to the origin.

If  $a = 1$ , then  $w_1$  becomes the extremal function for the class  $\mathcal{S}^*$ . For this function  $w_1$  given by (3.19), how can we consider the inverse function  $w_n = f^{-1}(w_{n-1})$ ?

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İSTANBUL KÜLTÜR UNIVERSITY, DEPARTMENT OF MATHEMATICS AND COMPUTER SCIENCE, ATAKÖY CAMPUS, 34156 BAKIRKÖY, İSTANBUL, TURKEY

*E-mail address:* e.yavuz@iku.edu.tr

KINKI UNIVERSITY, DEPARTMENT OF MATHEMATICS, HIGASHI-OSAKA, OSAKA 577-8502, JAPAN

*E-mail address:* shige21@ican.zaq.ne.jp